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13. ABSTRACT (Maximum 200 words)

ABSTRACT

This project concerns the exploration of two novel and enabling technologies: a self-collimated multi-wavelength laser (SCMWL), and the underlying binary superimposed grating (BSG), on which the SCMWL depends. The BSG is a multi-wavelength reflector which can be implemented by a convenient two-level etching process. The SCMWL makes use of BSGs to form a planar cavity with collimated multi-wavelength resonances. When combined with gain, the result is self-collimated multi-wavelength output.

We have demonstrated for the first time that both the BSG and the SCMWL concept work, through three proof-of-concept implementations in an optically pumped AlGaAs planar waveguide. These simplest-case devices exhibit multi-wavelength lasing at as many as 4 wavelengths, with channel spacings in accord with prediction. These preliminary results call for more exhaustive characterization, and pave the way for the implementation of electrically pumped SCMWLs with a greater number of wavelengths.

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Final Progress Report

Binary Super Grating (BSG) self-collimated multi-wavelength laser

Principal Investigator: **J.M. (Jimmy) Xu**

ARO Proposal Number: P-38889-EL   Grant Number: DAAG55-98-1-0435

FOREWORD

This project concerns the exploration of two novel and enabling technologies: a self-collimated multi-wavelength laser (SCMWL), and the underlying binary supergrating (BSG), on which the SCMWL depends. The BSG is a multi-wavelength reflector which can be implemented by a convenient two-level etching process. The SCMWL makes use of BSGs to form a planar cavity with collimated multi-wavelength resonances. When combined with gain, the result is self-collimated multi-wavelength output.

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Here we report on the results from this first year of exploration. While this document is entitled "Final Progress Report", work on this project is in fact on-going with ARO funding at Brown University, where Prof. Xu's lab has recently relocated. For administrative considerations related to this change of locale, we therefore submit this document as a final report for grant number DAAG55-98-1-0435.

STATEMENT OF THE PROBLEM STUDIED

The objective of this project was to design and fabricate the first proof-of-concept implementation of a novel self-collimated multi-wavelength laser (SCMWL), enabled by the novel binary supergrating (BSG), also developed by Prof. Xu's group. The BSG can be described as a sequence of equal-lines whose effective index is one of two values. The selection of these values, which can be represented as a sequence of 1's and 0's, lies at the heart of BSG synthesis. This concept can be applied in any waveguide structure, independent of material, and can produce nearly arbitrary diffraction characteristics. When combined

Multi-wavelength lasers (MWLs) have great potential in a variety of applications, enabling the increased transmission rates of wavelength-division multiplexing (WDM) systems, and enhanced operation in free-space settings such as range-finding, beam guidance, and infra-red counter-measures (IRCM). Ideally, MWLs should have low inter-channel interference (crosstalk), high power, low beam divergence for optimum coupling or free-space propagation, and be compact. In addition, it is highly desirable that any associated tuning circuitry be as simple as possible for ease of packaging and control.

No MWL achieves all these ideals, and in fact all previous MWL designs suffer from high divergence. The ideals of high power and low divergence are generally in contradiction due to the requirement of single-lateral-mode operation, which for existing MWLs restricts both current density and beam width. To overcome this, a design is required which simultaneously permits broad-beam collimation and monomode operation, with simultaneous emission of multiple wavelengths.

This can be achieved by exploiting the freedom afforded by planar propagation, by implementing BSGs in a planar waveguide to define a two-dimensional ring cavity as shown in Figure 1. When combined with gain, this leads to simultaneous multi-wavelength lasing, where the gratings define not only peak wavelengths but also beam divergence, leading to the attractive properties of self-maintained wavelength spacing (i.e. no drift-induced cross-talk) and self-collimation.

The operation of this device can be understood by first considering the diffraction characteristics of BSG-A in Figure 1, whose M diffraction wavelengths depend on incident angle θ according to:

$$\lambda_m(\theta) = 2\, n_{eff} \Lambda_m \cos(\theta), \tag{1}$$

where Λ_m represents the emulated grating pitches and n_{eff} is the effective modal index. The N diffraction wavelengths of BSG-B depend similarly on $\phi = \theta - 90^o$. The ring cavity design thus constrains resonances to wavelength/angle pairs which are simultaneously diffracted by BSGs A and B, as shown graphically in Figure 2. The result is a self-collimated comb of M x N wavelengths with self-maintained spacing: fixing the entire comb requires feedback monitoring of only a single channel.

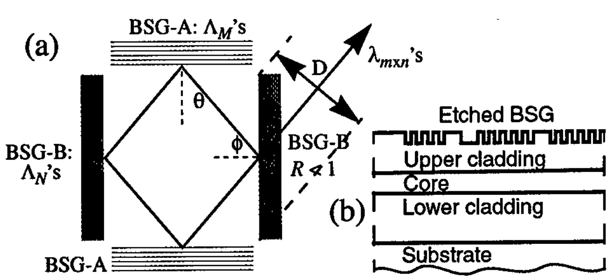

Figure 1. Schematic of SCMWL implementation: (a) top-view of structure with two twin BSGs; and (b) side view of etched-BSG implementation. Indicated paths correspond to peak of beam, which in fact fills most of inter-grating area.

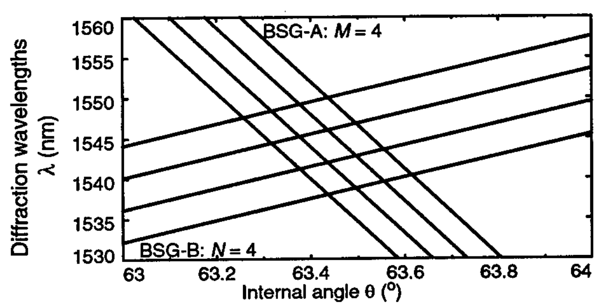

Figure 2. Diffraction wavelengths vs. internal angle for BSGs of a SCMWL. In this example, intersections correspond to 16 resonant wavelengths spaced by 0.8 nm in the 1.55 μm region.

SUMMARY OF MOST IMPORTANT RESULTS

Here we report on the first experimental evidence corroborating the novel concepts of the self-collimated multi-wavelength laser (SCMWL) and the binary supergrating (BSG), on which the SCWML depends. We have implemented proof-of-principle SCMWL designs with the top-view geometry shown in Figure 3, by fabricating BSGs in the upper cladding of an AlGaAs planar waveguide via electron-beam lithography followed by reactive ion etching.

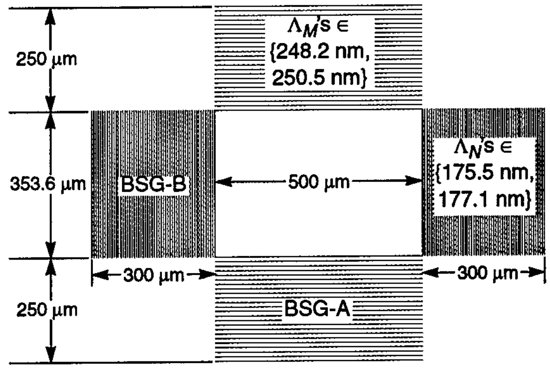

Figure 3. Top-view design of first-cycle proof-of-principle SCMWLs, implemented in AlGaAs planar waveguide with modal index 3.43 and gain at 980 nm from InGaAs QWs.

The number of wavelengths supported by the SCMWL is given by MxN, where M and N are the number of pitches emulated by each grating pair. For these first-cycle designs, M and N were chosen to have the simplest case values of 1 or 2, with the objective of verifying the underlying concept. In particular, BSG-A emulated M pitches in the vicinity of 249 nm (one or both of 248.4 nm and 250.5 nm), whereas BSG-B emulated N pitches in the vicinity of 176 nm (one or both of 175.5 nm and 177.1 nm). With the modal index n_{eff} of 3.43, this yields expected peaks in the region of 980 nm, within the gain spectrum of 20% InGaAs quantum wells located in the waveguide core. Three combinations of MxN were employed: 1x1 (single peak); 1x2 (2 peaks spaced by 6 nm); and 2x2 (2 interlaced pairs of peaks spaced by 6 nm).

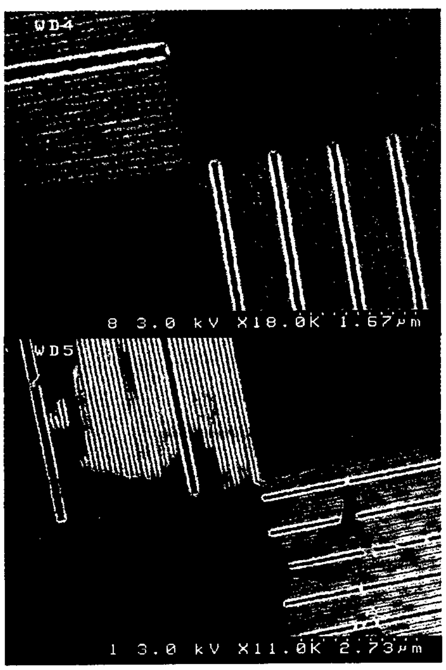

Figure 4. Top-view SEM images of test structures implemented in an AlGaAs planar waveguide: (a) relatively clean corner region; and (b) corner region with evident defects. Remarkably, both devices gave comparable performance, attesting to the robustness of BSGs.

Devices were first verified under SEM to evaluate grating quality. As shown in Figure 4, the results were mixed: some devices were clean, whereas others exhibited obvious localized defects. What is remarkable, however, is that all devices exhibited comparable performance, giving a direct indication of BSG robustness.

The MWLs were then pumped at normal incidence using ~1 μs optical pulses with a wavelength of ~750 nm and a peak power density of ~1 kW/mm^2. The output was monitored with a fibre placed near the wafer edge and directed to a monochrometer, where spectra were observed in real time using a diode array. Preliminary results are shown in Figure 5. The expected number of peaks are observed, and with the expected spacing.

The large amplified spontaneous emission (ASE) background is an expected consequence of optically pumping material outside the cavity region. The shift to longer wavelengths is due to heating. The observed linewidths are broadened by two limitations of our present setup: a diode array resolution of ~ 0.5 nm; and the temporal characteristics of the pump pulses, which are too long to avoid heating effects and exhibit considerable variation in peak power. Nevertheless, the experimental results of Figure 5 are a compelling confirmation of the SCMWL concept.

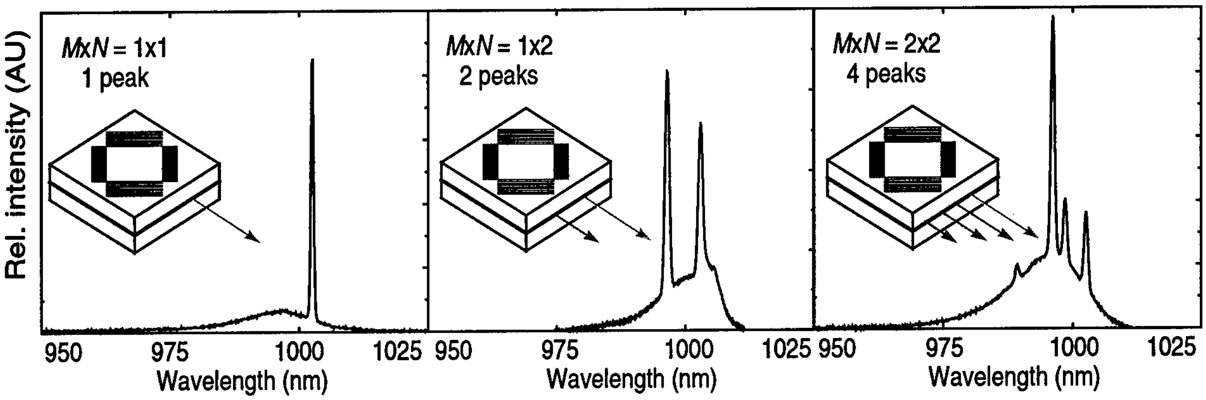

Figure 5. Spectra observed when proof-of-concept device is optically pumped, for (a) 1x1 device, showing 1 peak; (b) 1x2 device, showing 2 peaks; and (c) 2x2 device, showing 4 peaks. Prominent ASE background is an expected consequence of pumping much of the "bulk" crystal outside the resonant cavity. Peak width corresponds to resolution of diode array detector.

To gain insight into the operation of these proof-of-principle SCMWLs, the linear polarization of the output was observed, as shown in Figure 6. As can be seen, the output is not purely TE or TM, but is rather of mixed polarization, suggesting a coupling between TE and TM modes. TE-TM coupling is a known phenomenon associated with grating reflections in the neighbourhood of 45^o, as is the case here (internal angles of 54.7^o and 35.3^o). Polarization coupling can be useful: for example it does serve to stabilize gain-competition between TE and TM modes, and allows polarization-insensitive output.

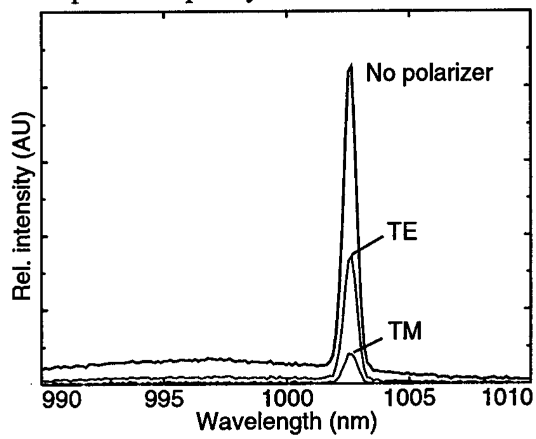

Figure 6. Polarization characteristics of 1x1 SCMWL, showing spectra for TE-aligned polarizer output, TM-aligned polarizer, and no polarizer.

In other cases, such as where pure TE output is desired, polarization coupling should be avoided. This can be accomplished by employing a cavity with a more extreme aspect ratio (which corresponds also to the ratio of the centre pitches of BSG-A and -B), whose internal angles lie further from 45^o. Fortunately, this is in agreement with the design rules for SCMWLs with larger numbers of wavelengths: for MxM channels with linear spacing, the cavity aspect ratio should be $\sqrt{M}$, yielding internal angles of $\operatorname{atan}\sqrt{M}$ and $\operatorname{atan}\sqrt{1/M}$. This will be explored further in subsequent implementations.

These preliminary results are restricted by the available apparatus, and by no means represent the performance limit of the MWLs. Our immediate next task is to re-engineer the experiment, along with the build-up of additional test equipment better suited to the task. In particular, we intend to invest in a pump source whose pulses are more uniform and sufficiently short to avoid heating effects. With this in place, we can properly tackle challenges such as resolving linewidth; clearly demonstrating simultaneous lasing; studying beam geometry at the output and within the cavity itself; and exploring the intriguing (and complex) question of modal interactions.

List of Manuscripts

SPIE '99 - Denver, CO, July 20-24, "Binary super grating WDM -- a new technology" (invited).

LEOS '99 - San Francisco, CA, Nov.8-12, "Self-collimated multiwavelength laser enabled by the binary superimposed grating: Concept, design, theory, and proof-of-principle experiment" (submitted).

OFC 2000 - "Binary super gratings -- an enabling technology for passive and active WDMs" (invited).

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Genlin Tan - Computer simulation and administration
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Report of Inventions

Multi-wavelength self-collimating lasers (patent pending).